DEVELOPMENT OF LARGE SCALE AUTOMATED AVALANCHE TERRAIN EXPOSURE SCALE (ATES) RATINGS IN COLLABORATION WITH LOCAL AVALANCHE EXPERTS

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ABSTRACT: The Avalanche Terrain Exposure Scale (ATES) is a terrain rating system developed in Canada to communicate risk due to snow avalanches to backcountry recreationists. While ATES is used widely in Canada for purposes of both recreation and industry, it has not been adopted in the United States, in part due to the large investment and manual effort required for avalanche professionals to create ATES maps at scale. However, recent developments in automated ATES models have opened up opportunities for large scale mapping using GIS and remote sensing methods. This paper describes the process we developed to localize the AutoATES model for different regions in the continental United States by engaging regional avalanche experts, and the subsequent improvements made to the AutoATES model to improve accuracy and practical applications for backcountry recreationalists and professionals. By implementing new methods for creating a forest density input layer and adjusting parameters of the Potential Release Area and Runout models based on local avalanche characteristics, we have extended the practical applications of AutoATES and taken meaningful steps towards generating ATES maps for large areas in the continental United States.

KEYWORDS: Avalanche Terrain Exposure Scale (ATES), AutoATES, Digital Maps, Forest Density, Localization.

1. INTRODUCTION

Digital maps are an increasingly common tool for identifying avalanche terrain. Slope angle, slope aspect, topographic and satellite imagery are all tools that, with appropriate time and practice, can aid users who need to navigate avalanche terrain. However, slope angle maps do not accurately capture all the variables that are important to safely navigate in avalanche terrain, and a better solution is needed to create visualizations that can aid recreationalists and professionals alike.

Previous research has developed automated avalanche terrain visualizations with digital mapping tools which have been used in trip planning products such as White Risk in Switzerland (Harvey et al. 2018). While this product has paved the way for developing avalanche specific digital mapping tools, the application of these methods is limited by the requirement of high resolution (5m) input data sets and the fact that the underlying models are based on proprietary software. Therefore, the cost of implementing these methods in the US is prohibitively high given the currently available data. In addition, the runout simulations used in the creation of the avalanche terrain visualizations target a frequent avalanche scenario, only simulating avalanches up to size D3 or less. This prohibits identification of areas that are completely safe from avalanche terrain because the longer runout distances of larger avalanches are not accounted for.

The Avalanche Terrain Exposure Scale (ATES) (Statham et al. 2006, Statham and Campbell 2023) was developed in Canada to communicate avalanche terrain risk. To date ATES has not been adopted at scale in the United States, in part due to the large investment and manual effort required for avalanche professionals to create ATES maps. However, recent developments in automated ATES (AutoATES) models (Sykes et al., 2023; Toft et al., 2023) have opened up opportunities for large scale mapping using GIS and remote sensing methods.

A foundational assumption of ATES and AutoATES is that it represents the *potential* for terrain to produce an avalanche and is agnostic of snowpack. It does not factor in aspect, wind scouring, or other factors that lead to lack of snow avalanches on a slope. While this

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presented some challenges for local experts who gave feedback based on known avalanche activity, we did not attempt to incorporate snow distribution or snowpack as a factor in this paper.

The only implementation of ATES in a product for recreational users in the United States is Beacon Guidebooks, who has been a partner in the localization work presented in this paper. Beacon uses ATES to describe avalanche exposure on individual ski lines, a different approach than our method for creating spatial ATES maps. This 'linear ATES' method is effective for communicating terrain hazard along specific routes but it lacks the flexibility of 'zonal ATES' ratings that cover entire regions. By providing ATES ratings for entire regions the zonal ATES method provides users the option to alter their terrain exposure by selecting an alternative route depending on current conditions and field observations. The ATES v2 technical model describes 'Route Options' and 'Exposure Time' as factors for delineating ATES ratings based on whether there are options to reduce avalanche terrain exposure (Statham and Campbell 2023). These attributes are much more logical to consider for linear ATES ratings, but zonal ATES ratings are unable to account for these factors. Instead, zonal ATES maps generated by AutoATES visualize the more objective parameters of the ATES model, but provide a high enough resolution for users to make exposure and route decisions on their own.

Our goal is to apply AutoATES to create widespread, high resolution, avalanche specific trip planning tools in the United States in collaboration with local avalanche centers. This paper presents our workflow for collecting feedback from avalanche centers on the AutoATES output, describes improvements made to the AutoATES model based on that feedback, and discusses issues around visualization of the output layers as well as education of users. The outputs of AutoATES that we are testing as trip planning tools include a potential avalanche release area layer, avalanche runout zone layer, and ATES classifications.

2. LOCALIZATION FEEDBACK PROCESS

Over the past year, we worked with avalanche professionals in Colorado, Montana, and Utah to gather local feedback on the AutoATES model in over 1.7 million acres, covering the extent of the forecast zones for the Crested Butte Avalanche Center (CBAC), Gallatin National Forest Avalanche Center (GNFAC), Utah Avalanche Center (UAC) Salt Lake Forecast Zone and select regions throughout Colorado Avalanche Information Center (CAIC) forecast area. We conducted four iterations of feedback with both CBAC and GNFAC, and as of writing have completed one round of feedback with UAC and CAIC. In reality, the amount of feedback collected does not encompass the millions of acres we generated maps for, but we found that focusing on a few key areas in a particular forecast region gave us enough information to make changes that improved the AutoATES output across the whole region.

Our localization process collects qualitative feedback from avalanche professionals on three outputs of the AutoATES model - the potential release area model (PRA), avalanche runout simulation (Runout), and the ATES classification model. For more in depth information about the open source AutoATES model see Toft et al. (2023).

Our order of operations to collect feedback from local avalanche experts focuses initially on the PRA and runout layers before evaluating the ATES output. By focusing on the upstream models in the AutoATES workflow first, we can make systematic improvements that impact the accuracy of all the AutoATES output regionwide. When reviewing the ATES maps themselves, reviewers apply the ATES v2 technical model (Statham et al. 2023) using their expert knowledge of the terrain.

Avalanche professionals who helped us review the layers could view the PRA, Runout, and ATES layers in onX Backcountry (a digital mapping tool). Most feedback was collected on the onX Backcountry web interface from a desktop computer, but onX Backcountry also has a mobile app that enables field-based feedback as well. Reviewers could mark waypoints to make notes in a target area, and draw polygons to describe runout paths or common start zones (Figure 1).

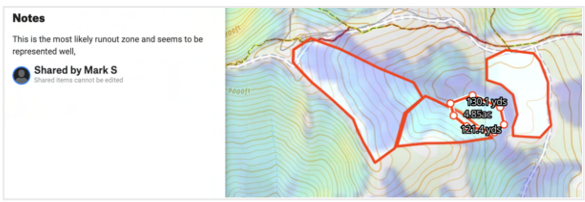

Figure 1: Polygons and notes on the Runout layer as part of the localization process.

These waypoints and polygons were then shared back to our team for review. Once we could generate a new version of the outputs based on that feedback, the workflow would repeat. No field work was required to gather feedback, and we estimate that reviewers could spend 1-2 hours and provide valuable feedback in targeted areas that led to large improvements in the model.

2.1 Potential Release Area

The PRA model is used to predict the location of avalanche start zones based on an elevation model and forest data. For each pixel in the study area the model determines the likelihood of being an avalanche release area based on the slope angle, wind shelter, and forest density using a fuzzy membership model (Toft et al., 2023). Cauchy functions for each parameter control the likelihood estimates and can be tuned based on feedback from local experts (Figure 2). For example, shifting the center of the slope angle distribution from 43 to 40 degrees can have a large impact on how low angle avalanche terrain is represented in the output. This can be useful in areas prone to widespread persistent weak layers where avalanches can release on lower angle slopes.

The PRA output is a continuous raster ranging from 0 to 1, with 0 indicating no potential for avalanche release and 1 indicating a very high likelihood of avalanche release (Figure 3). In order to use the PRA model as input to the runout simulation tool we apply a threshold to create a binary PRA raster. This threshold can be tuned for different locations or to capture different avalanche scenarios.

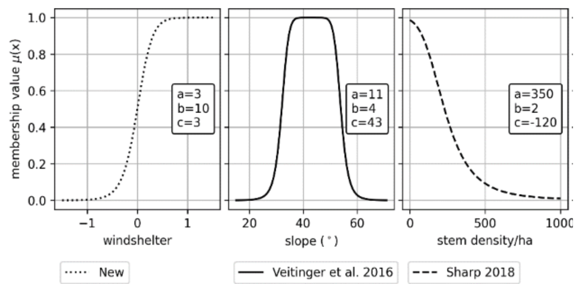

Figure 2: Cauchy functions for wind shelter, slope incline, and forest density (Toft et al., 2023).

We asked collaborators the following guiding questions about their area for review:

- Do areas that you know frequently release have a high value in the PRA layer?
- Are areas where you have observed infrequent releases under especially reactive conditions included (PWLs, remote triggering, lower angle slopes)?
- Does the value for that area appear to be above the PRA cutoff threshold?
- Are there areas in the forested terrain where PRA are either overestimated or underestimated based on your experience?

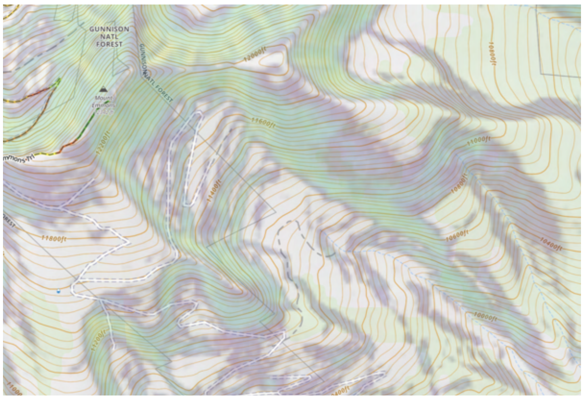

Figure 3: PRA visualization in the Crested Butte region. Lighter colors (yellow) indicate higher potential for avalanche release, and darker colors (blue) indicate lower potential.

2.2 Runouts

The runout simulation model we use is called FlowPy (D'amboise et al., 2022). We input a forest density layer (canopy cover), release area layer (PRA binary), and an elevation model and it calculates the runout path from every release area cell until it reaches a predefined alpha angle. We set the maximum alpha angle regionally based on local feedback, with the aim of capturing all avalanche runout zones, including historic events. By simulating longer runouts from higher magnitude avalanches, we aim to create maps that are more conservative and more usable compared to existing methods, even when the avalanche forecast is higher. FlowPy has an optional functionality to use the forest density layer to add friction to the avalanche flow and detrain snow from the flow which can result in a decreased maximum alpha angle in forested terrain (D'amboise et al., 2022). The output of FlowPy that we utilize are the maximum alpha angle and the maximum energy line height (z delta), which provides an estimate of potential avalanche size (Figure 4).

We asked reviewers the following guiding questions about their area for review:

- Does the maximum runout distance (alpha angle) in different types of terrain (big alpine terrain, shorter steep slopes) align with your local knowledge and observations?
- Are avalanches that release in forested terrain captured realistically?

- Are runout zones that extend into forested terrain captured realistically?

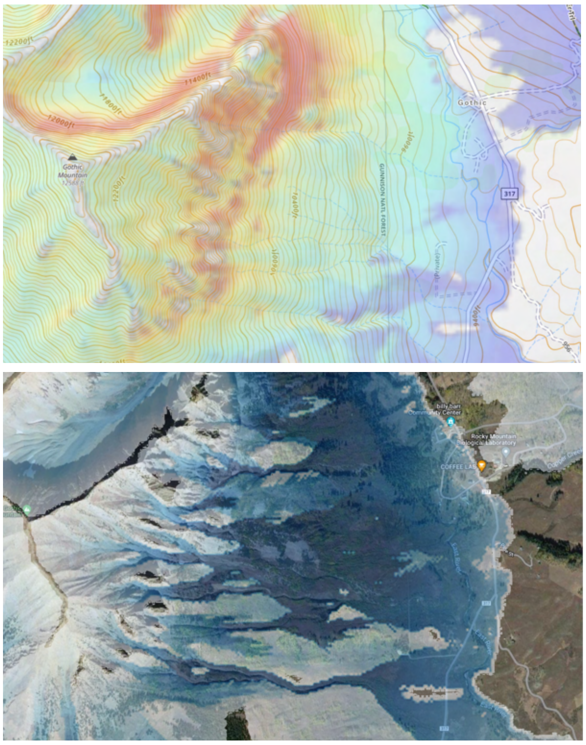

Figure 4: (Top) Alpha angle visualization of FlowPy runout. Cooler colors (blue) are lower alpha angle values (longer runouts) and warmer colors (red) are higher alpha angle values, therefore closer to start zones. (Bottom) Visualization of maximum energy line height, darker blue colors indicate runouts for larger avalanches.

3. UPDATES FROM LOCAL FEEDBACK

3.1 Forest cover input data

Based on feedback collected from multiple forecast centers, we found that the primary deficiency in the model accuracy was due to the resolution of the forest cover input data. Publically available forest datasets are typically low resolution (~30 m) and, based on our experience, tend to excessively interpolate across small openings in the forest cover, like avalanche paths (Figure 5). In the AutoATES workflow forest cover is used to damp potential release area probability and create a braking effect on the runout distance of small and medium avalanches (D'amboise et al., 2022; Feistl et al. 2014). Lower resolution forest input data can lead to inaccurate results within small clearings or well defined avalanche paths. Forest cover also plays a large role in determining the ATES classification, so improving this input data set improves every step of AutoATES.

To address this issue we developed a workflow to create 10 m resolution canopy cover data using Sentinel 2 multispectral satellite imagery. We used a random forest machine learning algorithm to classify the Sentinel 2 imagery into forest and non-forest classes based on the blue, green, red, and near infrared bands (Sykes et al., 2022). The forest classification algorithm was tuned, trained, and tested using manually generated polygons. To produce the final canopy cover percentage dataset we divide the number of forested pixels in a 5x5 neighborhood by the total number of pixels in a 5x5 neighborhood.

Integrating higher resolution forest input data into the AutoATES workflow extends previous research (Larsen et al. 2020) and increases the effectiveness of AutoATES where forest density impacts avalanche release area and runout behavior. Furthermore, the high temporal resolution of Sentinel 2 satellite data enables us to adapt to topography changes due to avalanche activity, forest fires or other events.

Figure 5: (top) Satellite image (middle) USFS canopy cover dataset based on Landsat imagery 30m (bottom) Sentinel 2 forest canopy cover dataset 10m

3.2 PRA model

The feedback we received about the accuracy of the PRA model varied based on region. We primarily focused on tuning the slope angle and forest density cauchy functions to get the PRA model to match local observations as closely as possible.

The main points of feedback we received for the PRA are:

- Small clearings in forested areas, or low density treed areas underestimated start zones.
- Lower angle slopes either overestimated or underestimated start zones due to default slope angle distribution in the PRA model.
- The PRA would overestimate release areas on slopes that typically do not hold snow due to local snowpack characteristics.

To address this feedback we re-ran the model with the 10m forest cover dataset mentioned in the previous section, and adjusted the slope angle distributions regionally. For instance in Crested Butte where persistent weak layers are common, the model was underestimating start zones in treed and lower angle slopes.

One piece of feedback we have not been able to address is the issue of the PRA model overestimating start zones in areas rarely if ever hold enough snow to cause avalanches. AutoATES is intended to identify areas where the terrain characteristics are capable of producing avalanches, but it does not incorporate snowpack characteristics directly. Therefore, it is common for the PRA model to overestimate start zones in areas where there is minimal snowpack, such as at lower elevations, solar aspects or wind-scoured areas. The practical impact is that the maps are very conservative in areas that do not typically hold enough snow to cause avalanches.

3.3 Runout model

Of the two FlowPy output layers (alpha angles and maximum energy line height), we have been exclusively soliciting feedback on the maximum alpha angle visualization. This layer has the most straightforward interpretation and is useful to relate field observations to the modeled output. However, the maximum energy line height (z delta) layer shows great promise for visualizing potential avalanche size and we plan to evaluate it more thoroughly in the future.

The main points of feedback we received for the runout were:

- Runouts are overestimated in heavily forested areas (Figure 6).
- Runouts are underestimated for large avalanche paths that start in the high alpine and run out to very low slope angles (e.g. 18°).
- Runouts were overestimated in areas where cliffs or trees typically reduce avalanche size.

During the initial phase of producing AutoATES maps we were not using the forest friction functionality of the FlowPy runout simulation software (D’amboise et al., 2022). This caused the runout simulations to be very conservative and model avalanche runout through lots of densely forested terrain. Once we developed the 10m Sentinel 2 canopy cover data we began testing the forest friction functions of FlowPy and found dramatic improvements.

The primary adjustments we made to the model based on the runout feedback were increasing braking effect for forest cover and adjusting default alpha angles to better match the characteristics of a region. To get the forest braking parameters correct, we produced many iterations with different parameters in forested runout areas and honed in on a set of parameters that most closely reflected the observed avalanche characteristics (Figure 6).

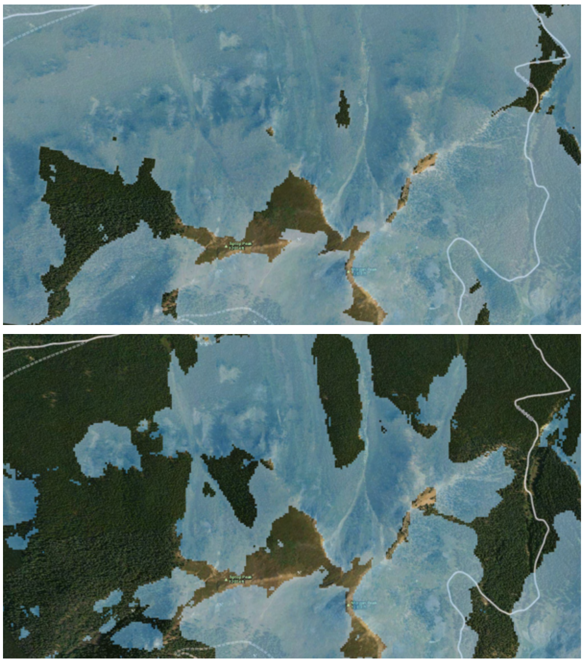

Figure 6: The first iteration (top) of the Runout vastly overestimated runouts in forested areas. Increasing the braking effect produced a much more realistic visualization of avalanche runouts.

With the forest braking parameters dialed in, we could also reduce the underestimation of long running avalanche paths by extending the runout distance (reducing default alpha angle) to capture more infrequent and large avalanches, and then rely on forest braking to damp the size of runouts in non-alpine areas and better funnel larger runouts to established avalanche paths.

3.4 ATES Classification

With the changes outlined above incorporated into the PRA and runout components of AutoATES, the ATES maps have systematically improved over time. Most of the improvements are due to the PRA and Runout updates, however we have also fine tuned slope angle thresholds, overhead hazard thresholds, and the way the forest layer is used in the ATES classification process.

Based on feedback that onXmaps has collected from its user base, it is desired by the public to visualize 'safe' terrain. This feedback encouraged us to include class 0 'non-avalanche' terrain in the AutoATES output. Our conservative approach to runout modeling, with the aim of capturing even the longest running avalanches, allows us to easily estimate class 0 terrain. We base the AutoATES parameters for 'non-avalanche' terrain on the ATES v2 technical model, by identifying areas with very low slope angles and that are well away from potential runout zones (Statham and Campbell, 2023). Further testing and development is necessary for class 0 terrain, but we are encouraged by the initial results and the potential to provide an easy decision-making tool for recreationists looking to completely avoid avalanche risk.

4. IMPLICATIONS FOR LARGE SCALE ATES MAPS

The practical applications of our work will be generating a combined visualization map of the PRA and Runout as well as an ATES map that we will make available to avalanche centers to display on their websites for their constituents, as well as within the onXmaps products. Our hope is that these maps will be a valuable decision making tool based on avalanche specific terrain information. There are three main considerations for bringing these maps to the broader public: how they are visualized, education around the ATES scale and confidence per local knowledge that the AutoATES model is as accurate as possible while erring on the side of conservative.

4.1 Visualizations

Introducing ATES to the recreation community - much less more advanced visualizations like the Runout layer - brings with it the burden of communication, education and distribution of the information. At onX, we conducted preliminary user interviews with backcountry skiers to understand general comprehension of the layers, both for substance and visualizations. While there is more work to be done, we found that the ATES maps required education and explanation before our interviewees found it comprehensible. Furthermore, the coloration of the layer caused some confusion, since ATES Level 3 "Complex" is styled in black, which with transparency on a digital map was perceived as 'no rating' (Figure 7). While we have not proposed changing the color scheme, new ways of representing transparent black on a digital map will need to be explored. Meanwhile, the runout layer was more intuitive as a 'heatmap' visualization and was more quickly comprehensible. Based on feedback, we are exploring improvements to the coloration of the layer to better indicate the distinction between start zones and concentrated runout areas.

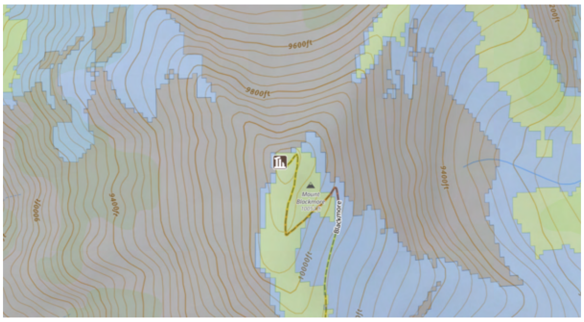

Figure 7: The coloring of Complex terrain (black) was interpreted by some test users as 'no rating'.

The ATES framework was designed to create large-area classifications for avalanche terrain, but the potential for much higher resolution maps from AutoATES poses new challenges for visualizations of ATES. The ATES maps reviewed in this work were unsimplified and have the same resolution as the input elevation data. This prompts new discussions about the ATES scale: what does a single 10m pixel of Simple terrain amidst mostly Challenging and Complex terrain mean for a user (Figure 8)? In previous work for visualizing automated avalanche terrain hazard (Harvey, et al. 2018), a continuous gradient was used, which abstracts a viewer's ability to know why a particular value for hazard was obtained, but reduces the ability to 'thread the needle' between different classifications.

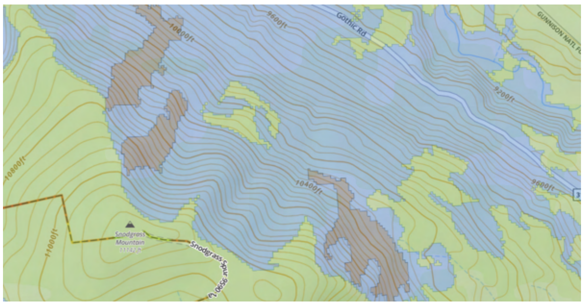

Figure 8: ATES layer of Snodgrass in Crested Butte. Pockets of Simple terrain within large areas of Challenging terrain potentially indicate to users areas of relative safety.

It is of interest to explore ‘fuzzifying’ the ATES boundaries to reduce the likelihood that a user will interpret the thresholds between ATES classes literally. Qualitative feedback of the ATES layers produced for this paper were both positive (it may represent smaller terrain features or ‘safer’ spots within complex terrain) and negative (it promotes threading the needle) for the higher resolution ATES layers, and further research with non-professional users is required to hone in on the correct visualization.

5. CONCLUSION

Digital mapping tools are becoming ubiquitous in the backcountry recreation community, and current tools for analyzing avalanche terrain require an in-depth understanding of avalanche mechanics, route planning, and the underlying technology to be reliable and useful. The work presented in this paper plots a path forward to creating large-area ATES maps and other avalanche terrain visualizations like Runouts and Potential Release Areas, with an eye towards productizing this information to be distributed and used by professionals and public alike. Significant improvements to the AutoATES model were accomplished: we improved our forest cover dataset by processing Sentinel 2 imagery, included forest friction in the runout simulations, and localized parameters for the PRA and Runout models for different forecast regions. By improving the model and focusing on a local feedback workflow, we are creating a replicable process for generating PRA, Runout, and ATES maps that can scale to the many different snowpacks and ecosystems across the continental United States.

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